Evaluation and Control of Vibration in Smart Composites with Delamination

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A B S T R A C T

This study presents a comprehensive investigation into vibration suppression of delaminated smart composite beams integrated with surface-bonded piezoelectric (PZT) actuators. A finite element framework utilizing ANSYS APDL was employed to model the modal, harmonic, and transient responses of cantilever beams under varying delamination conditions and control strategies. Closed-loop feedback vibration control with displacement signals was implemented through proportional–integral–derivative (PID) schemes, and the effects of individual control gains (Kp, Ki, Kd) were systematically examined. The results indicate that while proportional feedback control significantly improves damping and reduces rise time by over 40%, the integral and derivative components contribute minimal additional benefits. Modal analysis confirmed the optimum actuator voltages for vibration suppression, with double-patch PZT configurations demonstrating approximately 30% lower control voltage compared to single-patch arrangements, thereby enhancing energy efficiency. Transient analyses further revealed up to 85% reduction in steady-state vibration amplitude in delaminated laminates, affirming the efficacy of displacement feedback control. Overall, the findings establish proportional control in combination with optimally placed PZT patches as a practical, energy-efficient, and robust solution for active vibration mitigation in smart composite beams, even in the presence of structural delamination.

Keywords:

Delamination;
feedback control;
PZT;
PID;
control gain

1 Introduction

Smart composite structures comprising composite beams with surface-bonded or embedded sensors or actuators are being used in a wide variety of engineering applications such as vibration control, noise suppression, structural health monitoring, etc [1]. Recent investigations have demonstrated significant progress in active vibration suppression and noise control through piezoelectric actuation, adaptive control algorithms, and multiphysics finite element formulations. Several researchers have reported enhanced vibration attenuation through optimized smart material placement, advanced electromechanical coupling models, and intelligent control architectures. More recent developments have also focused on the dynamic behavior of damaged smart structures and efficient vibration mitigation strategies under complex operating conditions. These advances highlight the growing importance of integrating active control systems with structural damage assessment, thereby motivating the present investigation on vibration control of delaminated smart composite beams [23,24,25]. significance of dynamic analysis for laminated composite structures is becoming increasingly crucial due to its growing demand. Delamination is one of the most common damage mechanisms in laminated composite structures and refers to the separation or debonding of adjacent plies within a laminate. Such interlaminar damage reduces structural stiffness, alters natural frequencies, and may significantly influence the vibration characteristics and load-carrying capability of the structure [2]. Effective vibration control strategies are essential for improving the reliability and operational performance of composite structures. The integration of piezoelectric materials, which possess dual functionality as both sensors and actuators, with composite laminates is an effective approach for mitigating vibrations. Over the course of the previous decade, a multitude of methodologies have been put forth for the assessment of delamination phenomena and their control.

While the study of piezoelectric composites is a relatively new and developing research area, there is a scarcity of reported studies on its impact on delamination in smart composites and the extent of its efficacy in vibration control. Passive, active, and hybrid dampening reduce vibrations effectively. PZT-integrated smart composites increase passive and active vibration control for high-frequency excitations and low-frequency vibrations [3]. Active vibration control involves manipulating a system's vibration to reduce unwanted vibrations. The feedback control method, which uses sensors to measure vibration, a controller to process sensor data and generate control signals, and actuators to apply corrective forces or motions, is particularly effective in PZT-related vibration contexts. The adverse effects of delamination can be mitigated through active vibration suppression and structural response control. Feedback control systems use sensors to monitor system reaction and alter control inputs via a controller to reduce design deviation.

This paper includes the identification of the free vibrational characteristics of a delaminated smart composite beam including an embedded PZT actuator. It also examines the closed-loop feedback vibration control utilising various controllers and its parametric impact on the vibrational behaviour of the beam. The closed-loop control rule is integrated into the FE models through the utilisation of APDL. The simulations determine the control gains and the voltages for vibration control using piezoelectric actuation. Unlike previous studies that primarily focused on intact smart structures or employed conventional PID control without evaluating individual gain contributions, the present work investigates vibration suppression in delaminated smart composite beams using a finite element-based closed-loop control framework. The study systematically evaluates the influence of proportional, integral, and derivative gains, identifies the most effective controller configuration, and demonstrates that proportional control alone provides vibration suppression comparable to full PID control. Furthermore, the work establishes the energy advantages of double-PZT actuator configurations through reduced voltage requirements.

2 Vibration-controlling Techniques

Vibration management in delaminated composites is critical for ensuring structural performance and safety. Damping strategies may be passive, active, or hybrid, with PZT-based smart composites offering enhanced passive control at high frequencies and effective active control at low frequencies [4]. Active vibration control (AVC) involves deliberately modifying system responses to suppress undesired vibrations, with feedback control emerging as a particularly suitable approach for PZT applications [5]. Such systems employ sensors, controllers, and actuators to minimize deviations between actual and desired responses, thereby mitigating delamination-induced displacements and vibrations.

Among feedback strategies, PID controllers are most widely adopted [6]. The proportional component addresses instantaneous errors, the integral component compensates for cumulative errors, and the derivative component anticipates error trends. The selection and tuning of these terms depend on system characteristics and control objectives. In smart composite systems integrated with piezoelectric elements, PID-based feedback control has proven to be one of the most effective AVC techniques for achieving reliable vibration suppression.

2.1 Feedback Vibration Control

Feedback control systems use sensors to continuously measure system reaction and a controller to alter control inputs to minimise the change between desired and actual responses, as shown in Figure 1. The error signal shows the discrepancy between system vibration and desired vibration. We chose displacement signals from the feedback vibration control technique's strain, displacement, velocity, acceleration, and force signals because they are effective at controlling low-frequency vibrations and structural integrity [7], [8]. In displacement feedback, displacement measurements are often included in the feedback signal to determine the oscillating structure's position and counteract vibrations. These signals can be compared to a desired set point to provide an error signal. Often employed in feedback systems, PID controllers use error signals to change control operations to decrease deviation. The values of Ks and Kv were fixed at 1000 based on the recommendations of Refs. [9,10], where high amplification factors were employed to ensure adequate sensor sensitivity and actuator authority in displacement feedback control systems. Maintaining Ks and Kv constant enables the effect of the control amplification factor Kc to be evaluated independently. Therefore, only Kc was varied between 1 and 5 to determine its influence on vibration attenuation characteristics.

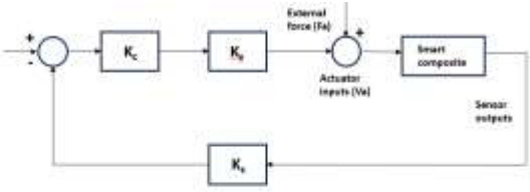

Fig. 1. Kinematics of the rth delamination at the ply level

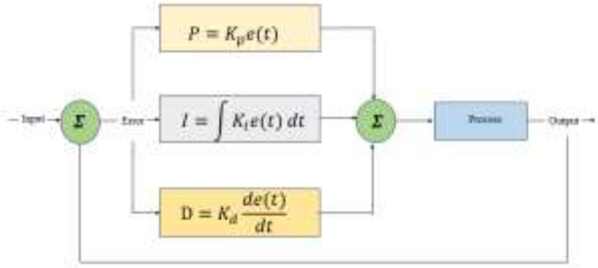

Fig. 2. PID controller block

2.2 Active Vibration Control using PID Controller

PID-based control is an effective technique for mitigating system vibrations induced by resonant frequencies. The PID controller algorithm, proficient in active vibration control, has three distinct control mechanisms: proportional control, integral control, and derivative control, denoted by the symbols P, I, and D, respectively. P is dependent on the present error, while I relies on the aggregate impact of prior errors, and D relates to the prediction, as shown in Figure 2. Future inaccuracies are projected based on the current rate of change. Piezoelectric components are utilised to mitigate vibration through a weighted aggregation of these three processes. The proposed design approach has the potential to save costs, improve stability, and is comparatively easier to forecast for smart structures [11].

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

where:

Kp = proportional gain controlling present error,

Ki = integral gain eliminating steady-state error,

Kd = derivative gain improving damping and reducing overshoot,

e(t) = tracking error,

u(t) = control signal.

The initial controller gains were selected as Kp = 1, Ki = 1, and Kd = 0.00055 following Ref. [12]. These values were subsequently adjusted iteratively to achieve stable vibration suppression and minimum settling time.

The control signal u(t) is transmitted to the system, yielding a new output. The freshly produced output is then sent back and compared with the reference to ascertain the new error signal (e). The controller computes the derivative and integral of the new error signal to obtain the revised value of (u).

2.2.1 PID Controller Characteristics

The feedback loop in a PID controller, as depi cted in the image, is employed to understand the effects of control parameters.
The variable e(t) in the picture denotes the error , defined as the discrepancy between the desired output value and the actual output.
The error signal e(t) is directed to the PID contr oller, which computes both the derivative and in tegral of this error signal to produce a control si gnal.
The created control signal will be transmitted to the system to decrease the error in the shortest t ime possible. The initial controller values for P, I, and D are set as 1, 1, and 0.00055, respectively [13]. They are adjusted as needed to achieve the appropriate damping efficiency.

The approach employs u(t) to represent the c ontrol signal given to the system, while Kp, Ki, a nd Kd signify the tuning parameters for proporti onal, integral, and derivative gains, respectively.
The control signal u(t) is transmitted to the syst em, yielding a new output.
The freshly produced output is then sent back a nd compared with the reference to ascertain the new error signal (e).
The controller computes the derivative and inte gral of the new error signal to obtain the revised value of (u) [13].

2.3 Dynamic Response of Delaminated Smart Composite under Transient Analysis

The transient response of composite beams embedded with PZT patches was analyzed to evaluate vibration control in delaminated smart structures. In the numerical model, incorporating parameters that represent sensors and power supply components is crucial, as the fidelity of the results depends on accurately replicating real-world system behavior. The overall system dynamics are strongly influenced by the sensor characteristics (Ks), actuator specifications (Kc), and power supply properties (Kv) [14]. Harmonic analysis was first performed over the frequency range containing the dominant natural frequencies of the delaminated smart composite beam. The displacement amplitudes obtained at resonance conditions were extracted and used as initial excitation inputs for the transient analysis. This procedure enables the transient simulation to represent realistic operating conditions corresponding to the most critical vibration modes. The feedback control algorithm was then applied to these transient responses to evaluate vibration suppression effectiveness under resonant excitation [15].

2.4 Vibration Control using PID

In applying PID control for active vibration suppression in smart composite structures, it is critical to consider the structural damping effects introduced by actuators, as these significantly influence the overall system dynamics and control efficiency [16]. To address this, a parametric investigation of damping coefficients was first conducted to assess their impact on dynamic behavior, followed by an open-loop analysis to guide controller design. Insights from the open-loop response were then used to optimize controller performance: the proportional gain was tuned to improve rise time, the derivative gain to minimize overshoot, and the integral gain to eliminate steady-state error. The controller gains (Kp, Ki, Kd) were iteratively adjusted until a satisfactory dynamic response was achieved. Displacement feedback was employed as the control strategy for implementing active vibration suppression [17].

2.5 Modelling Assumptions

The manuscript has been revised by explicitly stating the assumptions adopted in the finite element and control formulations. The assumptions include linear elastic behavior of the composite beam, perfect bonding between PZT patches and laminate, predefined non-propagating delamination, linear piezoelectric constitutive behavior, small deformation theory, constant material properties, ideal feedback control without measurement delay, neglect of environmental disturbances, and Rayleigh damping representation of structural damping.

3 Results and Discussion

It is imperative to evaluate the vibration control characteristics of the piezoelectric element and the impact of structural damping on the smart composite structure before implementing a PID controller. The vibration control properties of a piezoelectric device in passive open-loop control are examined using the Finite Element Method (FEM). A modal analysis, succeeded by transient analyses, is conducted under impulse loading to ascertain the modal frequencies and response characteristics.

A preliminary three-dimensional model of a composite cantilever beam featuring a singular piezoelectric patch is constructed to examine the effects of asymmetric coupling with the beam. A SOLID186 element comprising 20 nodes, each possessing 3 degrees of freedom, is employed to model the structure. The material and geometric characteristics of the smart beam are sourced from references in Tables 1, 2, and 3 [11-13]. The piezoelectric patch is modeled using a SOLID226 element, characterized by 20 nodes and four degrees of freedom (Ux, Uy, Uz, and voltage) per node.

3.1 Delamination Modelling

Delamination was modelled using the Cohesive Zone Modelling (CZM) approach as shown in Figure 3. The interlaminar region between adjacent plies was represented through cohesive interfaces governed by traction–separation constitutive laws. The CZM approach enables progressive degradation of interfacial stiffness and accurately captures the onset and growth of delamination. The laminate plies were modelled using SOLID186 elements, while the delaminated interfaces were represented through zero-thickness cohesive contact layers. The cohesive stiffness parameters and critical energy release rates were selected according to the values employed in the validated numerical model presented in the papers [26], [27].

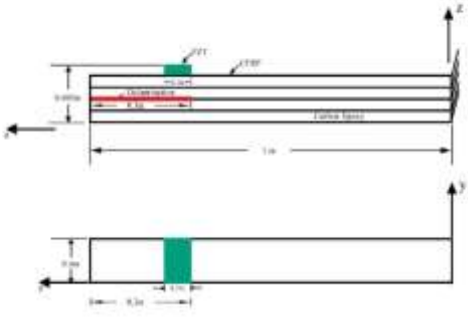

Table 1. Dimensions of composite beam and PZT patch

Particulars	'L' in m	'B' in m
Composite beam	1	0.4
Piezo patch	0.1	0.4

Table 2. Material properties of Carbon Epoxy [11]

Parameters	Values
Elastic Modulus in x-direction (Ex)	150 GPa
Elastic Modulus in y-direction (Ey)	10 GPa
Elastic Modulus in z-direction (Ez)	10 GPa
Poisson's ratio in x-y direction (γxy)	0.3
Poisson's ratio in y-z direction (γyz)	0.3
Poisson's ratio in z-x direction (γzx)	0.3
Modulus of Rigidity in x-y direction (Gxy)	7.1 GPa
Modulus of Rigidity in y-z direction (Gyz)	2.5 GPa
Modulus of Rigidity in z-x direction (Gzx)	7.1 GPa
Density	1600 Kg/m³

Table 3. Material properties of PZT [13]

Parameters	Symbols	Values	Unit
Density	ρ	7800	kg/m^3
Dielectric loss factor	tanδ	0.02	-
Compliance	S11	15	$\times10^{-12}$ m^2/N
	S22 = S33	19	
	S12 = S21	-4.5	
	S13 = S31	-5.7	
	S23 = S32	-5.7	
	S44 = S55	39	
	S66	49.4	
Permittivity	εT11	1.75	$\times10^{-8}$ F/m
	εT22	1.75	
	εT33	2.12	
Piezoelectric coefficient	d31	-2.1	$\times10^{-10}$ m/V
	d32	-2.1	
	d33	5	

Fig. 3. Optimized position of PZT on delaminated composite beam

3.2 Modal Validation

3.2.1 Convergence

The convergence study of a laminated composite beam with delamination for different mesh divisions is demonstrated in this section. As the number of elements increases, the responses change along with a simultaneous increase in the computational cost. But after attaining an optimum mesh size, the response remains the same, and the percentage difference in the subsequent steps decreases, as in Figure 4. To maintain the required accuracy and the minimum computational cost, this optimal mesh size is used throughout the analysis.

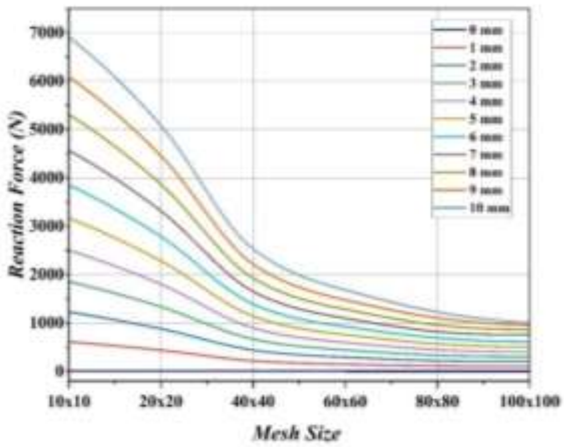

Fig. 4. Convergence test for various mesh densities

3.2.2 Grid independence study

Table 4. Grid independence study

Number of cells	Displacement (mm)	RF (N)
4800	10	1680.71
6400	10	1225.16
8000	10	1210.16

The grid independence analysis from Table 4 reveals that augmenting the cell count beyond

6400 does not substantially influence the displacement or reaction force (RF), signifying that the simulation results are numerically stable and that more mesh refinement is unnecessary for accuracy in this context.

3.2.3 Validation

For validation, the results of the delaminated smart composite beam with cantilever boundary condition, Simulated using a three-dimensional finite element model in ANSYS APDL, are compared with those obtained from the published experimental work [22] as shown in Table 5. The Kevlar/epoxy prepreg composite material is utilized for the same. The geometric characteristics of the plate are specified as the length in the x-direction, the width in the z-direction, and the thickness in the y-direction. The delamination model employed in this study comprises four plies, wherein delamination occurs specifically between the second and third plies. The composite beam model exhibits a ply thickness (t) of 1.5 mm, a length (l) of 350 mm, and a width (w) of 12 mm, with a crack length (a) of 0.03 m and a PZT patch of length 30 mm at a distance of 59 mm from the free end of the beam.

Table 5. Natural frequency

Set	Natural Frequency (Hz)	Natural Frequency (Hz) [22]
1	50.24	51.30
2	139.91	141.96
3	275.57	278.06
4	455.92	461.28
5	682.06	689.82
6	953.01	960.82

3.3 Modal Analysis

The study commences with a modal analysis of a finite element smart composite model. The first ten natural frequencies of the smart composite model are generated and given in Table 6. The highest natural frequency obtained from the modal analysis was 195.25 Hz (Mode 10). Accordingly, the transient analysis time step was selected according to:

$$\Delta t = 1/(20fh) \quad (2)$$

where fh represents the highest natural frequency considered in the analysis, ensuring adequate temporal resolution and numerical stability.

Table 6. Natural frequencies of smart composite structure

Set	Natural Frequency (Hz)
1	7.14
2	22.67
3	38.51
4	48.21
5	99.25
6	107.84
7	140.41
8	162.54
9	184.21
10	195.25

The outcomes derived from modal analysis provide a foundation for the subsequent dynamic analyses.

3.4 Effect of Structural Damping

The structural damping characteristics of delaminated smart composite laminates were examined through the implementation of a closed-loop vibration control system utilizing displacement feedback from embedded piezoelectric (PZT) patches functioning as both sensors and actuators. System responsiveness was evaluated by varying the displacement proportional gain (Gd) values, specifically at 0, 1, 1.5, and 2, as previously established [18]. Energy dissipation within the laminates was accurately modelled by incorporating Rayleigh damping coefficients in accordance with established formulations [19].

$$\xi = \frac{\alpha}{2\omega_1} + \frac{\beta\omega_1}{2} \quad (3)$$

where:

- C = damping matrix
- M = mass matrix
- K = stiffness matrix
- α = mass proportional damping coefficient
- β = stiffness proportional damping coefficient

The Rayleigh damping relation can be displayed:

$$C=\alpha M+\beta K \quad (4)$$

A delamination length corresponding to 30% of the beam span was selected because previous parametric investigations reported in the thesis demonstrated that this level of damage produces a significant reduction in stiffness and natural frequency while maintaining structural stability. Consequently, it represents a realistic moderate-to-severe damage scenario for evaluating vibration control effectiveness.

The proportional gain controller modulated the feedback voltage derived from the sensor layer to drive the actuator, thereby dynamically influencing the displacement response. Time-domain simulations for a laminate exhibiting 30% delamination were performed to elucidate the impact of different Gd values on vibration attenuation behavior.

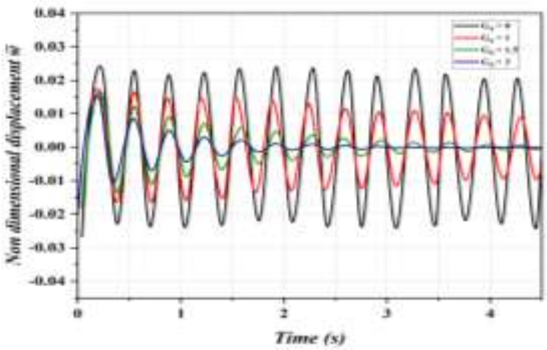

Fig. 5. Effect of structural damping

Figure 5 illustrates a clear trend of decreasing vibration amplitudes with increasing displacement proportional gain values. When Gd=0, the system operates without damping, resulting in persistent oscillations and elevated vibration amplitudes. Progressive increments in Gd to 1, 1.5, and 2 noticeably enhance the structural damping effect, which accelerates vibration attenuation and reduces amplitude over time. The results reveal that higher displacement proportional gain not only increases the effective system stiffness but also facilitates improved energy dissipation, promoting faster stabilization of the laminate post-disturbance. Overall, the displacement feedback control strategy achieves an approximately 85% reduction in steady-state vibration amplitude, thereby establishing its effectiveness for vibration suppression in delaminated smart composite laminates.

3.5 Dynamic Response under Transient Analysis

The transient analysis was performed with a time step of 0.007, determined in accordance with the first natural frequency of the smart composite beam obtained via modal analysis. The time increment (Δt) was established using the relation Δt=1/(20fh) [20], ensuring adequate resolution of the dynamic response for both open- and closed-loop displacement feedback configurations. Additionally, closed-loop investigations were conducted on cantilever composite beams featuring single and double collocated piezoelectric patches to capture the system performance under varying actuation scenarios.

3.5.1 Comparison of Open-loop and Closed-loop Vibration Control

The comparative results in Figure 6 distinctly highlight the advantages of closed-loop vibration control over the open-loop configuration in smart composite beams.

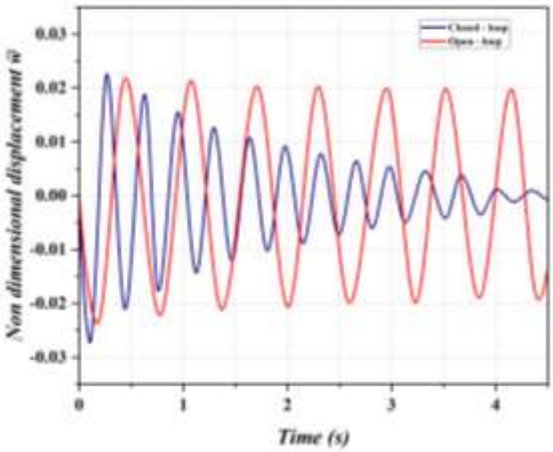

Fig. 6. Comparison of open-loop and closed-loop vibration control

The open-loop response reveals sustained high-amplitude oscillations at the undamped natural frequency of 7.14 Hz, signifying limited energy dissipation and poor inherent damping capacity. In contrast, the closed-loop system exhibits a pronounced and rapid attenuation of oscillations, with substantially lower vibration amplitudes sustained throughout the time history. This distinct improvement highlights the controller's ability to enhance effective damping and augment the overall dynamic stability of the structure. Accordingly, the closed-loop strategy demonstrates markedly superior performance in suppressing undesirable vibrations, thereby confirming its efficacy for vibration management in both delaminated and pristine smart composite laminates.

3.5.2 Closed-loop vibration control

Transient vibration analysis of the smart composite beam under closed-loop control was carried out using Rayleigh damping coefficients α=1.356 and β=0.0002, with the system excited at its undamped natural frequency of 7.14 Hz for comparison. The experimental configuration employed sensor and power amplification gains (KsKs and KvKv) fixed at 1000, while the control gain (Kc) was systematically varied in the range of 1–5. The optimal actuator voltage was identified through harmonic analysis, after which the influence of Kcon vibration suppression was evaluated. Notably, since the applied actuator voltage (Va) is directly proportional to the product KsKcKv, altering individual amplification factors while maintaining a constant product did not affect the net voltage input or the control performance. The time-history of tip deflection, illustrating the effect of varying Kc on the vibration response, is presented in Figure 7.

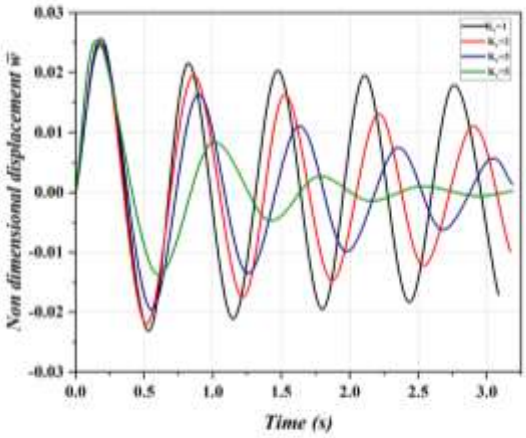

Fig. 7. Effect of control amplification factor (Kc)

The time-response results indicate that an increase in the control amplification factor (Kc) markedly reduces vibration amplitudes and accelerates the attenuation of transient oscillations. Higher Kc values (e.g., 3 and 5) yield significantly lower tip deflections relative to smaller values (1 and 2), thereby demonstrating enhanced vibration suppression. This trend highlights the strong dependence of actuator performance on the control gain, as Kc directly influences the output voltage and, consequently, the actuation efficiency. Optimization of Kc is therefore essential for achieving a more robust closed-loop response, enabling rapid stabilization and effective mitigation of vibrations in smart composite beams. These results underscore the critical importance of control gain selection in active vibration control for both delaminated and intact composite structures.

3.5.3 Active vibration control with proportional controller

Active vibration control was implemented using a proportional controller, with the proportional gain (Kp) systematically varied between 0 and 8. Variation in Kp directly influences system stiffness and responsiveness; higher values generally enhance damping and reduce rise time, although excessively large gains may induce instability or amplified oscillations. For each selected gain, the displacement feedback loop was activated, except in the baseline case (Kp=0) where no control action was applied. The corresponding tip displacement responses were recorded and compared across all gain values, as illustrated in Figure 8.

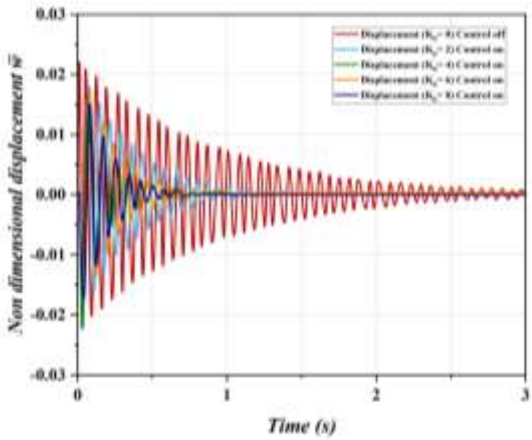

Fig. 8. Active vibration control with proportional control

The results show that increasing the proportional gain (Kp) substantially accelerates vibration attenuation and reduces rise time. Higher Kp values yield more rapid stabilization of the beam response, whereas the uncontrolled case (Kp=0) exhibits sustained oscillations with slow decay. These observations confirm that proportional control enhances system responsiveness and significantly improves vibration suppression in smart composite beams.

3.5.4 Active Vibration Control with Proportional-integral Controller

Active vibration control of the smart composite beam was implemented using a proportional–integral (PI) controller, with the proportional gain (Kp) fixed at its maximum value and the integral gain (Ki) varied between 0 and 8. Variation in Ki enables the mitigation of steady-state errors through error accumulation;

however, excessively high values may degrade transient performance or induce instability if not appropriately balanced with Kp. Displacement feedback was employed to regulate the actuator voltage for suppressing vibration amplitudes and improving system stability. The transient responses corresponding to different Ki values were recorded to assess the influence of integral control on the overall vibration mitigation performance.

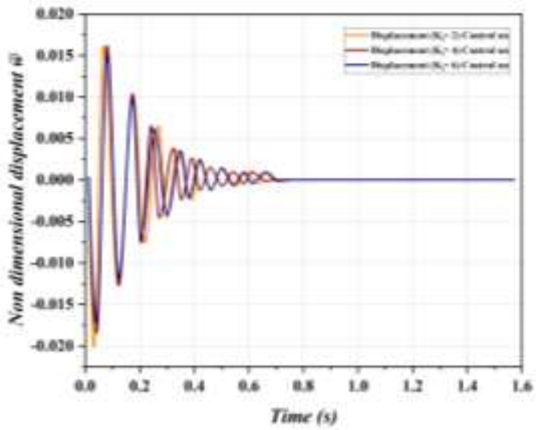

Fig. 9. Active vibration control with proportional-integral controller

The results presented in figure 9 indicate that increasing the integral gain (Ki) yields only a marginal reduction in rise time, with limited influence on overall vibration attenuation. Moreover, larger values of Ki tend to slow the transient response, thereby reducing system responsiveness to external disturbances. These findings suggest that, although the PI controller preserves system stability, the integral component contributes minimally in this application, with the principal advantages of active vibration control being predominantly achieved through proportional action.

3.5.5 Active Vibration Control with Proportional-integral-derivative Controller

Vibration control of smart composite beams using a proportional–integral–derivative (PID) controller employs the combined action of proportional (Kp), integral (Ki), and derivative (Kd) gains. In this scheme, displacement feedback is processed through each control component to generate the actuator voltage. The proportional term provides rapid correction based on displacement magnitude, the integral term mitigates steady-state errors through error accumulation, and the derivative term responds to the rate of displacement change, thereby enhancing damping and suppressing excessive oscillations. By tuning Kd and incorporating derivative control, the system effectively anticipates rapid vibration changes, leading to improved stability and superior transient performance.

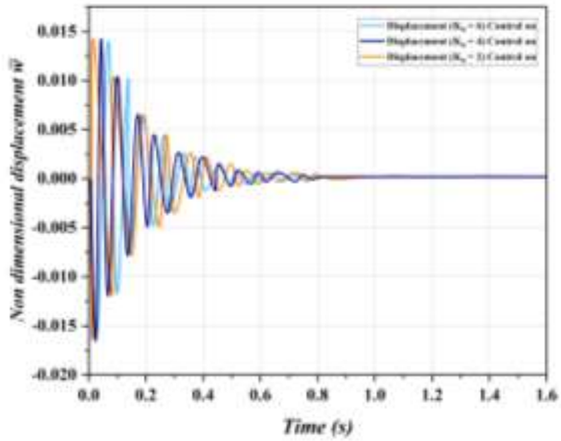

Fig. 10. Active vibration control with proportional-integral-derivative controller

The results in Figure 10 show that although the PID controller provides rapid vibration suppression and a smooth, stable transient response, its performance is largely comparable to that of the proportional controller alone. The close similarity in vibration attenuation and stabilization across different derivative gain (Kd) values indicates that proportional control by itself is sufficient for effective vibration management in this case, with the added complexity of PID control offering limited practical benefit.

3.5.6 Active vibration control comparison

The results presented in Figure 11 indicate that proportional control dominates the vibration suppression process. This behaviour is attributed to the fact that the primary objective of the controller is attenuation of oscillatory displacement rather than elimination of steady-state error. Since the vibration response is predominantly transient and oscillatory, the proportional gain directly generates corrective actuation forces proportional to displacement error. The integral component contributes little because the system exhibits negligible steady-state offset, while excessive integral action may even introduce slow oscillatory behaviour. Similarly, the derivative component provides limited additional damping because structural damping and piezoelectric feedback already contribute significant energy dissipation. Consequently, the improvements achieved by Ki and Kd are marginal compared with the dominant influence of Kp.

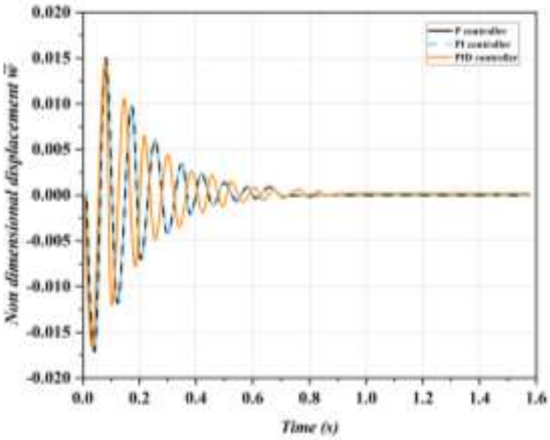

Fig. 11. Active vibration control with proportional-integral controller

The PID controller demonstrated slightly improved transient characteristics, including reduced overshoot and enhanced stability margins. However, the reduction in vibration amplitude was found to be comparable to that achieved using proportional control alone. Consequently, the proportional controller represents the most practical control strategy for the present smart composite configuration owing to its simplicity, reduced computational requirements, and comparable vibration suppression capability.

4 Conclusions

This study investigated the influence of PZT patch configurations and feedback control strategies on the vibration and dynamic behavior of smart composite cantilever beams through modal, harmonic, and transient analyses. The results demonstrate that the integration of bonded PZT patches with a closed-loop strain feedback system provides effective vibration suppression and enhances dynamic stability, even under delamination conditions. The key findings can be summarized as follows:

Modal analysis: The optimum control voltage required for effective vibration suppression was identified for the first three modes in both single- and double-patch configurations. The double-patch configuration achieved an approximately 30% reduction in the optimum control voltage compared to the single-patch configuration, highlighting improved energy efficiency.

Transient analysis: Variation of control gains confirmed that the proportional controller (Kp) contributes the most significant effect, reducing rise time by more than 40% and enabling rapid system stabilization. In contrast, integral (Ki) and derivative (Kd) control components had negligible influence on system performance, offering no significant improvements over proportional control alone.

Overall, the findings establish that proportional feedback control, coupled with energy-efficient PZT patch arrangements, provides a practical and robust strategy for active vibration mitigation in both delaminated and intact smart composite beams.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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